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JET PROPULSION

Journal of the

AMERICAN ROCKET SOCIETY

VOLUME 21

~~1950~~ 1951

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JOURNAL OF THE
AMERICAN ROCKET SOCIETY

Number 84 ROBERTSON YOUNGQUIST, *Editor* March, 1951

TASKS WE FACE

By F. Zwicky

Fellow ARS, research consultant and member of Advisory Board, Aerojet Engineering Corporation, Azusa, Calif., professor of astrophysics, California Institute of Technology, Pasadena, Calif.

Dr. Zwicky recommends "morphological thinking" as a new tool for scientists and inventors which opens up vistas to the inquiring mind that remain hidden to unorganized thought. He outlines the five essential steps of the methods and shows how successfully the method was applied to invention of new jet-propulsion engines, several of which he describes. He also discusses the potentialities of a new field of research called "metachemistry."

THE PURPOSE of this address is to discuss some of my personal ideas about the future developments in jet propulsion. Such a discussion obviously requires some measure of speculation and prophecy about inventions still to be made and new devices to be constructed. In contrast to the writers of science and engineering fiction, we are interested not only in the visualization of new developments but also in the quantitative appraisal of their possible value as well as in the practical steps which must be taken to insure the realization of these developments.

It is often thought by the uninitiated that it suffices to have a really good scientific idea or a good technical invention to convince every reasonable man of its value and thus to achieve its practical use. But this is far from true. Especially if the new ideas deal not only with specific items, but involve large-scale mass invention of many devices or refer to very general new methods of operation, the obstacles which will be encountered are great and are often similar to those met with in the course of attempts to establish new sociological institutions, new methods of education, and the like. These obstacles have their origin in ignorance, inertia, and the most dangerous, the spirit of jealousy resulting in actual sabotage. Laymen would certainly be most surprised to learn to what extent human frustration hinders the processes of science and technology, even where developments are concerned whose value should be obvious to almost

Address presented at the Annual Banquet held during the 1950 Annual Convention of the AMERICAN ROCKET SOCIETY, Hotel Statler, New York, N. Y., Nov. 26–Dec. 1, 1950.

anyone. These difficulties grow to staggering proportions when large-scale scientific and technical planning is involved. It is precisely with this type of planning that I shall here be concerned with. I shall describe to you later, a new mode of thought which furnishes the adequate scientific basis for such planning. I have called it morphological thinking since it is concerned with the intrinsic structural characteristics of the formalism and of the contents of thinking. You will find that the essence of morphological thinking is relatively easy to grasp, although its systematic application needs considerable training. Morphological thought and action are the distinctive tools of truly free men. The goal of this type of thought is the visualization and the analysis of all possible solutions of any given problem without regard or reference to standards of value. No technical, personal, or group prejudices must be allowed to stand in the way of a complete morphological analysis and the subsequent realization of those solutions which are best suited to achieve a certain prescribed purpose. Later I shall discuss the application of the morphological method to some specific problems such as the visualization of all possible propulsive power plants which are activated by chemical energy, or the classification of all possible types of telescopes, and so on. It will be found that this task is not an insuperable one and that in many cases it is not even a very difficult one. Likewise, the actual technical realization of the best solutions found often is not too difficult in itself. Even on such a colossal problem as the reconstruction of the planetary system, in which jets are destined to play a major role, one might confidently start work tomorrow since enough knowledge is available already to guarantee that very little of the work will be found later on to have been done in vain. The main problem involved thus is not of a technical nature, but it has its roots in widespread shortcomings of the human mind and of the social structures of mankind. Obviously then, for anybody who is vitally interested in large-scale planning, the elimination or neutralization of the principal obstacles which stand in the way of the realization of great plans, is of prime importance.

The analysis of the obstacles mentioned is not simple. In fact, the obstacles are so great that a realistic estimate of any conventional method of attack reveals these to be quite impotent. Personally, I have felt for a long time that short of some unforeseen miracle, modes of thought or action must be developed which are far more powerful than anything hitherto known. To cope with this desperate situation, I have spent my major efforts during the past 30 years to develop such modes of thought and action. After glimpsing the solution dimly off and on in the tantalizing fashion of spotting a passing object through a soiled window of a railroad coach, I feel that I have finally found the philosopher's stone in what I call the "morphological outlook and method." As could be expected from a general tool of this sort, it promises to be of decisive help

in the offensive against human frustration. It also proves extremely powerful in the solution of general scientific and technical problems. In fact, the only aspect in this whole development which I do not cherish lies in the inevitable expectation of watching a great waiting horde of dubious characters attempt to blackmail morphology into the service of their small and unsavory aspirations. With the vultures all around them, constant vigilance is the price free people must pay, and it is the least price which they can pay.

Before describing the principles of morphological thought and some of the results achieved, I proceed with the brief mention of the major dark clouds on the present horizon, dark clouds which must be dispelled lest we intend to court complete disaster.

Four Dark Clouds

The dark clouds which I am thinking of are the more ominous since, in a way, they all hang together, reinforcing their individual dangerous effects through mutual vicious interactions. They originate from four circumstances which are not really new in character. Because of certain accelerated developments, these clouds have grown in importance so enormously that they have become characteristic for our age. The four phenomena which I have in mind are the following.

1 There exists today no subject which would excite the imagination of men in a positive way, stimulating a constructive and happy life. The universal appeals of religion, art, political freedom, and science have faded to the vanishing point. There remains only the universal negative appeal of misery, unhappiness, and frustration which has made possible the unprecedented ascendancy of all destructive forces.

2 The universal sense of frustration has resulted in the emergence of dismally unhappy men who either actively or passively wish for the destruction of the world. Miserable individuals like Lenin, Hitler, Stalin, and their satrap murderers have never seen a sunny day. They consequently built uρ the most elaborate systems for the only purpose of taking prolonged revenge on every happy man and leading the world to its final destruction. There are also millions of small frustrated fry in every country on earth, on both sides of the iron curtain, who are no asset at all to the democratic way of life. Although these individuals do not have enough energy to build up an active system of murder, they nevertheless would enjoy seeing all people made miserable whom they envy for having tasted some measure of human contentment. That sad character known as the "Hollywood pinko" and fellow traveler perhaps is the best example of a frustrated shrimp who lives a life of more or less quiet desperation, hoping and working for the day when he will get even with everybody. This type of individual is to be found everywhere. In government,

business, and at the universities he has quietly, unobtrusively, and always under the guise of the humanitarian flag, obstructed progress toward true freedom. He has effectively sabotaged the preparedness against the red menace within and without and has furthered the cause of those who would work toward the destruction of man.

The problems which we face because of the entrenchment of mass murderers back of the iron curtain, are enormously enhanced by two more circumstances. These are:

3 The effects of increasing population. Overpopulation has existed in the past but continues to plague us in an ever aggravated form. It is not usually thought that overpopulation is a severe problem in the western world. However, this is a relative appraisal. Indeed, the complications of modern life in the democracies of the world are such that they sap an immense amount of energy from human sources which should be available to fight the world's arch criminals. Individual tasks such as sanitation, food processing, general transportation, and automobile traffic in particular, education, health, taxation, law and order are growing to be of immense complexity unless procedures and methods will be adopted which are far more effective than anything used in the past. The morphological method which we shall discuss provides a first ray of hope.

4 One of the most peculiar problems of our age is that science is completely out of hand. This means that there are no scientists and not even any groups among them who master all of science technically and much less so organizationally. The reason for this state of affairs is of course twofold. In the first place science has grown so fast that rightly or wrongly, I think the latter, men have given up hope of being able to know it all. In the second place, and this is dangerous, government restrictions in almost all countries have introduced severe obstacles to any attempts at universal knowledge.

If universal knowledge is not available to enlightened and constructive men, many of their efforts to cope with the ills of the world must of course be doomed to failure.

Conventional Methods Are Insufficient

The four problems which I have mentioned must be solved in two stages, the first of which involves a holding action while the second is constructive action.

Obviously, from what we have said, the world is in danger of complete confusion and collapse. Although we think we know why and what should be done, there is not enough time to build a completely new world before the old one collapses. Therefore, the necessity of a holding action. We must, by fighting aggressors, preserve democracy as it is now, although it may not be perfect. Or more generally, we must preserve humanity and

the earth itself from complete destruction although both may be far from perfect.

After we have staved off complete disaster, and even before, we must get to work on building up a new and really decent free world.

Now you may ask, and rightly so, who is going to perform such Herculean tasks? Indeed, to make a long story short, there are only a few individuals in the world who can be of any help at all in the way of initiating large-scale programs of planning and action. Disregarding for the moment all of the men of ill will, most of the others are simply tired. Their efforts to earn their livelihood, attend to their families, take care of all the minor and major difficulties and tragedies of personal and of community life leave them with no energy to put their shoulders to the wheel of sociological tasks demanding grueling efforts. There thus remain relatively few individuals to start the good work. But even these individuals can only spend a fraction of their time and energy, and past experience shows that too often do they get crushed themselves. It is obvious that conventional methods are not good enough to allow these men of action to work effectively. Theirs must be methods which multiply the all-around technical and human efficiency many fold. It is this consideration which started me thinking and which, after some fumbling, led me to the development of the morphological mode of thought, planning, and action.

The Morphological Method

This method, as stated, is concerned with the totality of all of the solutions of a given problem. Its formalism and its detailed application have been described previously (1).[1] We shall therefore restrict ourselves to a brief sketch. The method proceeds as follows.

1 An exact statement is made of the problem which is to be solved. For instance, we may wish to study the morphological character of all modes of motion, or of all possible propulsive power plants, telescopes, pumps, communication, detection devices, and so on. If one specific device, method, or system is asked for, the new method immediately generalizes the inquiry to all possible devices, methods, or systems which provide the answer to a more generalized request.

It will be found that the task of formulating the initial statement or definition of the problem on hand is far more exacting than most investigators not acquainted with the new method are inclined to think. In fact, one is hard put to find in the existing literature satisfactory definitions even of well-known devices like pumps, stationary power plants, telescopes, and so on. The exact definition of apparently simple devices like injectors will be found to be a most difficult task and I doubt whether the combined common sense and sophisticated knowledge of any group of men would suffice to produce such a definition.

[1] Numbers in parentheses refer to bibliography on page 20.

2 The exact statement of the problem to be solved, or the precise definition of the class of devices to be studied, will reveal automatically the important characteristic parameters on which the solution of the problem depends. For instance, in the case of telescopes, some of these parameters are the location of the telescope (medium in which it is embedded), the nature of the aperture A, the recording device R, the nature of the changes to which the light is subjected from A to R, the motion of the telescope, the sequence of operations, etc. The second step thus involves the study of all of these significant parameters.

3 Each parameter p_i will be found to possess a number of different independent irreducible values $p_i^1, p_i^2 \ldots, p_i^{ki}$. For instance, the parameter "motion" of a telescope may have the independent values p^1, p^2, p^3 = translation in three directions; p^4, p^5, p^6 = rotatory motions; p^7, $p^8, \ldots, p^{12}$ = oscillation in the first six motions, etc. These matrices are written in the following scheme

$$
\begin{array}{l}
[p_1^1, p_1^2, \ldots\ldots\ldots\ldots p_1^{k_1}] \\
[p_2^1, p_2^2, \ldots\ldots\ldots\ldots p_2^{k_2}] \\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
[p_n^1, p_n^2, \ldots\ldots\ldots\ldots, p_n^{kn}]
\end{array}
$$

If one element is encircled in each matrix and all the circles are connected, every resulting chain of circles represents one possible solution of the original problem. The above scheme of matrices, if used to construct an n-dimensional space, leads to a "morphological box." The analysis is complete if either one or no solution will be found in every drawer of the box.

It is exceedingly essential that up to this point no questions be asked as to what value one or the other solution may have. Such premature curiosity almost always defeats the unbiased application of the morphological method. However, once all of the solutions are found, one must know their relation to any given set of adopted performance values.

4 The determination of the performance values of all of the derived solutions represents the fourth major step in the morphological analysis.

Lest one wishes to get lost in an enormous confusion of details, the performance evaluation must be carried out on a universal, although necessarily simplified basis. This is not always an easy task.

5 The final step involves the choice of particularly desirable special solutions and their realization.

The conviction that all solutions can be realized is inherent in morphological thought. It may, of course, happen that some among the many solutions are of a relatively trivial nature.

Sociological and Technical Applications

As I have stated, the morphological method was invented and developed primarily to cope with the severe and all-important sociological problems which I have discussed. It is not too much to expect that the method will actually prove its unique value in this direction, because:

A The morphological mode of thought and action is something new about which everybody can think, talk, and act. It covers all phases of life and therefore is the most universal subject available. The morphological view not only holds that every man is unique, irreplaceable, and consequently a genius, but it also helps each individual to realize this genius and thus to become his true self, avoiding all of the pitfalls of frustration and tragedies resulting therefrom.

B The morphological method of defense against the dictatorial menaces, whether they be of the red or of other varieties, is the only one feasible in a free country. In a democracy it will never be possible to be prepared by constantly training millions of men and constantly being ready with tremendous numbers of war machines. Democracies must be ready with the greatest number of truly superior weapons and devices. Only the morphological method of research and of invention can guarantee that this potential superiority is achieved at all times.

C The handling of all of the problems attending overpopulation and overindustrialization and mechanization falls naturally into the realm of morphological planning. In this relation a remark may not be superfluous concerning the advisability of doing any general planning at all. Such planning as is done by political parties, dictators, prejudiced groups in government, and the like is rightly looked upon with great suspicion. It cannot be overemphasized that morphological thought restores planning to its rightful place. The trouble with all other systems of planning is that they seem to be invented for the benefit of pressure groups and more or less narrow-minded ideologies. The morphological method in its essence does not allow such prejudices. It becomes actually inoperative when such prejudices enter upon the scene. Their presence is thus automatically detected.

D Finally, morphology makes possible a new type of education and the rebirth of the universal man and scientist. In his haste for the achievement of false values man has literally left education lag a thousand years behind the time. Morphological education takes its start from the profound conviction that every individual is unique, and in his special way, a genius. It therefore establishes an entirely new and never yet tried basis for education which aims at the liberation of all men through the realization of their genius. How, on this basis, all knowledge accumulated in the past comes within the mastery of capable individuals will be elaborated in another place.

In view of the dire situation in which we find the world, one is of course

tempted to plunge full force into sociological problems, that is, the reconstruction of governments and of human society in general. Although no chance must be missed to act wherever the opportunity is favorable, a full-fledged "morphological offensive" is inadvisable until the morphological method has established its worth through achievements which are indisputable. This would seem the easiest in the field of science and technology. Results in this field are also the most impressive as far as the general public is concerned. Another consideration is that the so-called specialists can do any general morphological planner a great deal of harm unless the latter can match them in their own fields. This fact necessitates that such a planner must be capable of practically matching all specialists. This task obviously cannot be achieved by anybody except a true master in morphological thought.

One of the problems before us is therefore to show that, armed with the morphological method, one may enter any field one pleases and show the specialists that they have become musty and that there are new fields under the sun as well as right under their noses.

A second task is to train morphologists at the universities, in industry, and in government. At the present time the new method is used by but a handful of men. Many more will have to become convinced of its power through its actual successful application.

Problems to Which Morphological Thought Has Been Applied

There are, in particular, three types of generic problems which the morphological analysis attempts to solve. These are:

1 How much information about a certain limited set of phenomena can be obtained with the help of a given class of devices? Or, stated differently, what devices are necessary to obtain all of the information about a given set of phenomena?

2 What is the sequence of all effects issuing from a certain cause?

3 Deduce all of the devices of a given class, or all of the methods of a given class or, generally speaking, all of the solutions of a given definite problem.

We proceed to illustrate these three cases through the use of some specific examples.

Totality of the Perturbations in the Atmosphere

A problem of type 1 is as follows. Is it possible to obtain fairly instantaneous records of all of the essential disturbances in the atmosphere which lie in a cone subtending not too great a solid angle? The records are to be made with one telescope or a small number of telescopes.

The answer to this question is in the affirmative. Obviously, what we ask for is condensed information on a great number of phenomena taking place simultaneously in the atmosphere. Among these phenomena are

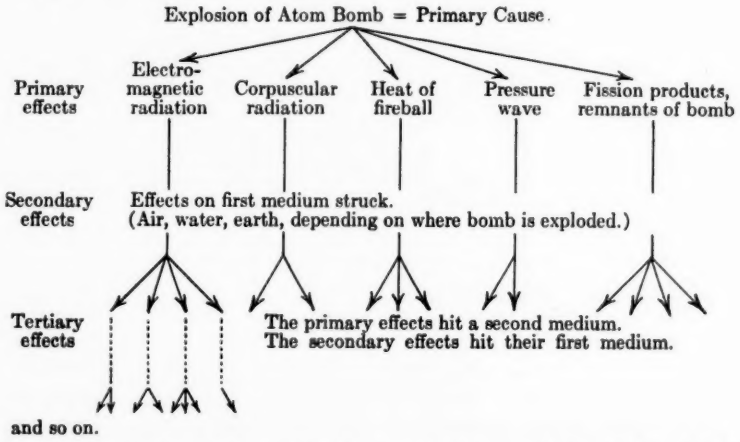
fluctuations in pressure, density, and temperature, convection currents, turbulence, oscillations, and relative changes in the concentration of the constituents of the atmosphere. One therefore expects much when one hopes to analyze all of the effects mentioned on one single photograph. It is a typical achievement of morphological thinking to have demonstrated that this is actually possible. In fact, all of the results achieved by moving-picture cameras, combined with sets of instruments carried aloft by high-altitude balloons which are being tracked, can be concentrated into single photographic records taken by telescopes stationed on the earth. For a detailed description of how such spectacular results are achieved through a morphological analysis of all possible telescopes, we must refer to the detailed treatments in the literature (2).

Totality of the Effects Issuing from Some Primary Cause

What we seek here is a family tree interrelating effects and causes.

A typical question is, for instance: What are all of the effects of a bomb or more specifically of an atom bomb, which is defined as an instantaneous phenomenon involving nuclear transformations of macroscopic quantities of matter?

The hereditary chain is somewhat as follows:


Explosion of Atom Bomb = Primary Cause.
Primary effects
Electro-magnetic radiation
Corpuscular radiation
Heat of fireball
Pressure wave
Fission products, remnants of bomb
Secondary effects
Effects on first medium struck.
(Air, water, earth, depending on where bomb is exploded.)
Tertiary effects
The primary effects hit a second medium.
The secondary effects hit their first medium.
and so on.

This hereditary tree is of considerable complexity. In the first place it will be noticed that each primary effect must, with a view to the subsequent effects, be subdivided into various ranges not only of different intensity but also of different quality. There are, in principle, three independent parameters for the electromagnetic radiation, namely, wave length, spectral intensity, and polarization. The case of the corpuscular radiation is vastly more complicated since one more parameter enters, namely, the type of particles which may be protons, electrons, neutrons, and so forth.

Each primary phenomenon acts successively on everything in its way which may be air, water, earth, and all animate and inanimate objects populating the earth. At each stage the physical characteristics and conditions as well as the location of the original matter present are altered and new types of matter are created. These act as additional sources of trouble for all matter encountered later.

The morphological knowledge of the effects of bombs is, of course, necessary both for a truly effective defense against them and also for their really effective offensive use. Many of the wild discussions which at the present confuse all issues could be silenced if some government agency or private group of citizens undertook a morphological analysis of the effects of atom bombs.

The Totality of All Jet Engines Which Are Composed of Simple Elements and Activated by Chemical Energy

In this address I wish to emphasize in particular that historically the first systematic and complete morphological analysis is that of the "totality of all jet engines." In many ways this is not an accidental fact. Indeed we knew at the beginning of the war that in the United States we were pitifully far back of the Germans and that only superior thinking could bridge the gap.

A simplified analysis was consequently carried out which resulted in the tabulation of 576 jet engines composed of simple elements. We recall that the aeroresonator was among them and that some financial support was received by the author from the Navy in January, 1944, to build such an engine, although many experts in the field expressed disbelief in its operability. The advent of the V-1 buzz-bomb engine six months later fully vindicated our confidence in the power of the morphological method. Actually it turned out that Archimedes, had he used the method, might have invented an aeroresonator burning charcoal. Attached to a suitable wooden board, such a device would have made possible the first powered heavier-than-air craft. It is thus almost unbelievable that all highbrowed science and engineering sophistication could have missed out on the aeroresonator for centuries. Under these circumstances we may expect that in the morphological box of the jet engines there are still many treasures hidden which no engineer or scientist has as yet thought of. In fact, I claim that nothing can be thought of which is not already waiting for us in the box.

I shall describe briefly what the morphological box of jet engines today looks like. I then shall proceed to discuss a few of the jet engines which are destined to play a role in the near future.

The essential parameter matrices and their elements, which I have used in the construction of the morphological box, are as follows:

$[p_1^1, p_1^2]$ = intrinsic or extrinsic chemically active mass
$[p_2^1, p_2^2]$ = internal or external thrust generation
$[p_3^1, p_3^2, p_3^3]$ = intrinsic, extrinsic, and zero thrust augmentation
$[p_4^1, p_4^2]$ = internal, external thrust augmentation
$[p_5^1, p_5^2]$ = positive and negative jets
$[p_6^1, p_6^2, p_6^3, p_6^4]$ = nature of the conversion of the chemical energy into mechanical energy
$[p_7^1, p_7^2, p_7^3, p_7^4]$ = vacuum, air, water, earth
$[p_8^1, p_8^2, p_8^3, p_8^4]$ = translatory, rotatory, oscillatory, and no motion
$[p_9^1, p_9^2, p_9^3]$ = gaseous, liquid, solid state of propellant
$[p_{10}^1, p_{10}^2]$ = continuous and intermittent operation
$[p_{11}^1, p_{11}^2]$ = self-igniting and not self-igniting propellants

This, if no internal contradictions were present, would make possible

$$2 \times 2 \times 3 \times 2 \times 2 \times 4 \times 4 \times 4 \times 3 \times 2 \times 2 = 36{,}864$$

pure-medium jet engines containing single simple elements only and being activated by chemical energy. However, there are some internal restrictions which, as the reader will find out, cut the above number to 25,344 possible simple engines.

Generally, any special propulsive power plant is described by a combination matrix which contains one element of each of the characteristic parameter matrices p_1. The morphological analysis subsequently proceeds as follows. A schematic sketch of every propulsive power plant is made and its mode of operation is described. A general performance analysis is carried out. This can be done relatively simply through the use of the universal thrust formula which the author has developed for the purpose (1). All performances are then intercompared in a special type of topological performance diagram or representation. Finally, special engines are chosen which are best suited for the realization of certain required purposes, and the construction of these engines is undertaken.

In the following I can only mention a few of the possible engines. I choose some which demonstrate that the morphological analysis opens up vistas which remain hidden to unorganized thought which leaves invention up to chance.

Some Special Propulsive Power Plants

The "Isothermal" Rocket Engine

The morphological study has shown that there are four and only four reversible and thermodynamically most efficient conversions of chemical energy into mechanical energy. Of these, only the adiabatic expansion is commonly used in rocket engines. This process involves chemical reaction in the thrust chamber and subsequent expansion through a nozzle. The generation of dangerously high temperatures is inevitable. Another of the four conversions is the isothermal expansion. This involves low temperatures only, but it is a process which must be achieved through

properly timed injection, reaction, and expansion taking place continually along some sort of a suitable duct. The study of what I call "continuous chemical reaction along the flow" of a gas or a liquid is thus destined to result in the construction of quite unconventional motors. Some motors of this type have already been built and successfully operated. Generally speaking, however, much remains to be done on the synthesis of new propellants and on their reaction speeds before semi-isothermal processes can be properly exploited for the generation of propulsive power.

The Interplanetary Aeroduct or Ramjet

This is the device which morphologically may be designated as

$$\{p_1^3, p_2^1, p_3^3, p_4^1, p_5^1, p_6^1, p_7^3, p_8^1, p_9^1, p_{10}^1, p_{11}^1 \text{ or } p_{11}^2\}$$

The principal point of interest is the presence of the element p_1^2 in the above matrix. This means that we derive our chemical energy entirely from the surrounding medium and that our jet engine is one which operates although it does not carry any propellants with it at all. Its "specific impulse" thus is at all times infinitely large.

It is commonly thought that the energy from the sun's rays is effectively stored only in the plants. This energy is available either from present processes or from those which have stored the energy in the past and which we now exploit in the deposits of coal, for example. The heat absorbed by the atmosphere, the ocean, and the earth's surface is not usually considered as being easily available for technical exploitation and especially not for the activation of propulsive power plants. The reason for this lies in the fact that heat can only be used to produce mechanical energy if large differences in temperature exist in adjacent localities. This is not usually the case. In contradistinction to this, much of the sun's radiation impinging on the very highest strata of the atmosphere is not absorbed only to heat these strata. Atoms and molecules rather are excited and ionized and new molecules are formed. All of these processes store the energy in such a way that in principle it can be made use of in its entirety. It also appears certain that the percentage of the excited elementary particles is large, while the energy available per particle is tens to hundreds of times as great as the energies available in ordinary chemical reactions.

There are thus two tasks before us. In the first place we must find out, through high atmosphere research, the nature and the number of the excited particles. In the second place, we must learn to de-excite them properly and use the energy gained in aeroducts, aeropulses, and other devices for the generation of propulsive power. This new field of research I have proposed to name "metachemistry." In this direction, in my opinion, lies the real future for vehicles to leave the earth. Metachemistry indeed is full of promise far beyond anything ordinary chemistry can achieve. Metachemistry actually, for purposes of propulsive power

is even superior to nuclear energy which in no sense of the word can be considered as freely available.

Intensive work in the line of metachemistry should therefore be promoted with the greatest industry. It will eventually make possible duct-like motors, swallowing the excited and inert components of the upper atmosphere and expelling them at greater and greater speeds, which will thus extract propulsive power from the atmosphere. Such a device may be made to circle the earth at higher and higher levels and escape ultimately into interplanetary space without any discomfort being suffered by the passengers because of any high accelerations.

In the line of obtaining enough information for interplanetary travel I started in 1945 a program of testing the upper atmosphere with ultrafast particles ejected from shaped explosive charges. This program, which was well on the way to success, has temporarily been stopped because of the interference of all sorts of difficulties, personal and otherwise, which are at the present beyond my control.

The Aeropulse and the Rocket Pulse

Returning to some less sophisticated devices, I wish to put in a good word for my first love among the jet engines. As I mentioned before, I picked this engine out of the morphological box in 1943. My reasons were simplicity of the device, great range of adaptability, specific impulse superior to that of the aeroturbojet, and possibility of lateral scavenging. This latter feature allows increased amounts of air to be mixed with the fuel without resorting to larger cross sections of the device. This in turn means higher propulsive thrust without increased drag.

Since the aeropulse achieves high thermodynamic efficiency through cascading of pressures, rather than through the use of mechanical devices such as compressors, the exact timing of all physiochemical processes is imperative. With ordinary fuels, such timing could not so far be achieved. A research program on new fuels and their kinetic chemical characteristics is therefore required to achieve the results sought for.

Countless engineers and scientists have held and probably still believe that with good sense and intuition the aeropulse could be built and efficiently operated without previous expenditures for basic research. Here we have one of the classic examples of unfounded optimism which in the last few years has cost far more due to losses by complete failures than even a most elaborate research program would have amounted to. My prediction still stands that no sledge-hammer artist will build an efficient aeropulse.

The rocket pulse actually is not one of the engines contained in the original morphological box. This propulsive power plant is a combination engine which belongs to the subclass of the interfacial jet engines. For instance, a steam locomotive uses the oxygen of the air to burn coal but gen-

erates its thrust by pushing against the earth. It is therefore an air-earth interfacial engine. In the same way, an ordinary ship's propulsive power plant is an air-water interfacial engine. The rocket pulse is one of the simplest air-vacuum interfacial jet engines. In this device a certain percentage α_1 of the necessary oxidizer O_2 is taken in from the air while the remaining percentage α_2 (not necessarily O_2) is carried by the vehicle itself. If $\alpha_2 = 0$ we have an aeroengine, while if $\alpha_1 = 0$ the device becomes a pure rocket. For the rocket pulse we have both $\alpha_1 \neq 0$ and $\alpha_2 \neq 0$. This device can be made to operate, for instance, by injecting simultaneously but intermittently a self-igniting combination of a suitable fuel and oxidizer. With proper design of the thrust chamber, the reaction products may be overexpanded and the resulting underpressure will introduce a charge of air whose oxygen and inert components may, during the next explosion, be used for the oxidation of extra fuel and for the internal augmentation of the thrust. In principle, the specific impulse of the rocket pulse can be made to vary between that of ordinary rockets and that of aeroengines mixing the largest possible amounts of air with fuel. A guess may be ventured that with practical designs the most useful range of applications of the rocket pulse will be around a specific impulse of $I_{sp} \cong 1000$ sec. One of the great features of this device is of course its self-pumping characteristics. Generally speaking, because of its much higher specific impulse, it should be most useful in replacing self-contained jet motors in rockets, considerable fractions of whose trajectories lie in the air.

Hydroengines

It is in the analysis of underwater travel that the morphological method has removed some of the greatest obstacles from the engineering mind. The morphologist boldly asks the question whether or not it is possible to "open up the ocean" in the sense that we may at will "see" and travel through it, live, and operate in it. Obviously, the achievement of these possibilities would be of immense importance for man's aspirations in peace and his defense against destructive forces in war. The resources hidden in the oceans at all depths and especially the prospect of mining along their floors suggest tremendous potential developments.

Even a superficial inspection of those compartments in the morphological box bearing the parameter $p_7{}^3$ = (hydro-) reveals that the hydrojet engines are destined to do exactly what is expected, that is, to open up the oceans in all of the aspects which I have mentioned.

While the mechanical problems in the field of hydrojet engines would not seem to offer any too great obstacles, much work remains to be done on the chemistry, thermochemistry, and kinetics of hydrofuels, as well as on their large-scale production before the day arrives when the exploration of the ocean at all depths will have become a Sunday afternoon's undertaking.

Terrajet Engines

As we have become aware by now, morphological thought does not stop at anything. Among the large-scale media through which travel may be of interest, the solid earth for obvious reasons is not the last. Resources of all kinds in a "thin" layer near the surface of the earth have been exploited by cumbersome methods for centuries. The question is, whether here also we are in for a revolution. The morphological analysis of the problem answers this question in the affirmative. The realization of the dream, however, will no doubt involve considerable work along the lines of exploring the geochemical and physical constitution of the earth in different regions, the production of earth reactive chemicals, or for short, terra fuels, and the fascinating and not quite obvious task of conceiving and constructing terrajet engines of proper design and efficiency. Here lie problems which will tax the ingenuity and skill of the best.

Electrochemical Conversion

The direct conversion of chemical energy into electrical energy is used on a small scale only in various types of batteries. Century-long attempts have failed in solving the famous problem of the "carbon cell" in which coal would be reacted with the oxygen of the air to produce electric current directly, efficiently, and on a large scale (3). Because of these persistent failures, the possibility of using the electrochemical rather than the conventional thermomechanical conversion for the production of propulsive power is hardly ever thought of. I think this is a grave mistake, and renewed efforts should certainly be made with the direct large-scale generation of electrical from chemical energy.

Auxiliary Problems in Jet Propulsion

We have already mentioned implicitly that the development of various propulsive power plants involves the following steps:

1 Conception, design, construction, and testing of jet engines.
2 The synthesis and production of propellants.
3 The thermo- and electrochemistry of the propellants.
4 The chemical kinetics of the propellants.
5 The design and construction of all auxiliary equipment such as propellant storage equipment, feed systems, pumps, and controls.
6 The development of proper instrumentation and of test equipment.

The morphological analysis of all of these problems is of great help but has not in any sense progressed as far as the thinking on the mechanical aspects of propulsive power plants. Here, therefore, open happy vistas for the scientifically minded young engineer.

Various Uses of Jet Propulsion

We must not forget that we are really not done with everything after we have put into operation one or the other type of jet engine. The invention of ever new applications for these engines is naturally one of great fascination. I have not carried out the morphological analysis of all of the uses jet engines can be put to. So all I can offer is a few quite unrelated suggestions.

A preliminary morphological classification of the uses of jets might be as follows.

1 Use for propulsion, that is, to change or maintain position, to change or maintain velocity, to change or to maintain acceleration of a given body which we generally call a vehicle. These applications are well known to the members of the American Rocket Society.

2 To generate permanent mechanical changes in various bodies. Outstanding examples are the processes of destruction, cutting, etc., on the one hand and the building up of materials on the other hand.

In both fields of applications tremendous possibilities open up to the imaginative mind. For those interested, I might suggest that they start visualizing jets of all dimensions from the microscopic through the macroscopic ranges and up to cosmic jets such as we observe in the explosions of novae and of supernovae. In these stellar outbursts, masses of the order of the sun's mass are ejected with velocities which are a considerable fraction of the velocity of light, that is, of the order of many thousands or even tens of thousands of kilometers per second.

Starting with microscopic jets, there are all of the numerous devices like cloud chambers, discharge tubes of all kinds, cyclotrons, betatrons, synchrotrons, linear accelerators, and so on, in which elementary particle beams and jets are used in innumerable experiments on nuclear and atomic physics. All of these devices were invented helter-skelter. They are of great enough importance to have netted their originators a number of Nobel prizes. Much remains to be done, however, and for the morphologist so inclined, there lies an immense and as yet sparsely plowed field.

Coming to "colloidal" jets, those ejected from shaped charges armed with various solid, and in particular with metallic inserts are the best known because of their armor cutting qualitites. Particles in these jets reach velocities of many kilometers per second. These particles flying through air or through denser media melt and evaporate. They reach thus the stage of "ultraflight." This is a mode of motion in which particles change their physicochemical properties along their trajectories. As I have pointed out on several occasions, particles of this kind may be made to leave the earth permanently. They can thus be used as artificial earth-launched meteors and may serve in many ways in the investigation of the highest strata of the earth's atmosphere and of all planetary bodies in the solar system as well as of the nature of the electromagnetic fields in interplanetary space.

Bigger jets with the masses ejected amounting to from 1 gram per sec to say, 1 ton per sec, are the ones we are most familiar with. Those among you who are interested in new applications will not overlook the fact that ordinary jets can be used not only for propulsive purposes, but also for all sorts of operations of cutting, heating, pumping, welding, as well as for some most sophisticated processes of accelerated diffusion and chemical segregation.

Finally, there remains the problem of whether or not man will ultimately be able to handle jets which approach the proportions of those produced in more or less minor stellar eruptions, and perhaps even those we watch in novae and supernovae. One of the vistas opened up by such achievements would be the reconstruction of the whole planetary system. Whether or not this will be feasible in the near future depends on success or failure in the development of powerful chemical, metachemical, and nuclear propellants.

Morphology of Propellants

The basic chemistry and physics of jet propulsion belong to the most neglected aspects of this new field. A morphological study of the chemistry of propellants has never been carried through, and the thermochemistry and especially the chemical kinetics of the potentially useful reactions are in the first stages of development. These, however, are now well started and enough highly competent men are available to carry these investigations to a good end.

Similar optimism is not yet justified in the fields of metachemistry and nuclear propellants. Here lie some of the greatest possibilities.

Metachemistry is concerned with:

(*a*) The stabilization in bulk of highly excited and usable metastable states of elementary particles, atoms, and molecules. The goal is usable energy contents per gram or per cc which amount to tens and even hundreds of kilogram calories rather than one or at most a few kilocalories as in ordinary chemicals.

(*b*) The use of excited particles freely available in the upper atmosphere and perhaps in interplanetary space and the atmospheres of the other planets. This, as we have mentioned, opens up possibilities superior to those afforded by nuclear reactions, since, in principle, infinite specific impulses are possible while no nasty parasite effects need be taken care of. Even for the practical use of nuclear energy, the production of intermediate metachemical propellants may be the most useful procedure.

Metachemistry, although it can do much, still can hardly help us on truly cosmic problems. For these, nuclear energy must be considered.

Morphological thought admits of no obstacles which are man-made and due to inertia, prejudice, weakness, or plain ignorance. Unless very defi-

nite reasons exist why a certain thing cannot be done, a morphologist must proceed with his analysis. A typical case in point is the present status of nuclear energy production. As far as is known to the general public, the main efforts are being concentrated on the use of a few easily fissionable elements as well as on some restricted processes of fusion to be used in a hydrogen bomb. Even without any further evidence, morphologists will hold that all fission processes as well as the fusion of all sufficiently light elements can be used unless some laws of nature can be pointed out which definitely prohibit the realization of these processes.

The problem before us is to learn how to "ignite" on a macroscopic scale the processes of nuclear fusion. I am certain that the morphological analysis will result in the discovery of a number of ways to achieve such ignition without using a fission bomb. Strenuous efforts should therefore be made in this direction before those who wish to annihilate us find the solution by some unpredictable chance move.

The realization of nuclear fusion will have the following consequences:

1 It will provide us with unlimited power supplies.

2 These power supplies are so vast that the reconstruction of the planetary system may be viewed as a realistic possibility. In our imagination we may visualize bringing the various planets into the earth's orbit. Tremendous lopsided nuclear fusion explosions on these planets can accomplish that. The resulting jets can likewise be used to decrease the masses of the large planets and to increase the masses of their satellites so that all of these bodies shrink or grow to resemble the earth. It will be especially important to have the surface gravitation of all bodies of similar value and to endow them with atmospheres similar to that of the earth.

3 There is one danger, however. This is, that through poor handling of the operations, or maliciously, the earth might be itself exploded. The true morphologist thus will be concerned with the stabilization of large bodies against nuclear fusion as well as with the processes of ignition. Because to him, to explode the earth by a mistake would be poor style indeed.

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PRINCIPLES OF ROCKET-TURBOPUMP DESIGN

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A rigorous analysis of the significance of all the variables that influence the design of rocket turbopumps is not readily practicable. This paper discusses the formulation of approach in the design of the different components which make up the complete unit, with particular emphasis on pump parameters. The suction specific speed of the pumps is shown to be the controlling parameter in determining a minimum fixed-weight design for both auxiliary and prime rocket power plants, whereas such factors as pump efficiency, turbine efficiency, and propellant performance must be individually treated, depending on the specific application.

THE recent increase in the use of rocket power plants has led to the establishment of detailed operating requirements. In turn, these requirements establish the boundary conditions within which the pumps and turbines must perform. Until recently, there was not sufficient information available to make possible a clear definition of the limits of operation of power plants and components. As a consequence, the pumping units and other components were usually designed for arbitrarily fixed operating conditions rather than for the optimum conditions. In addition, overemphasis was often placed on the development of some particular characteristic which, on final analysis, was found to be of minor importance.

In this paper, attention is directed to the turbopump of the rocket power plant. An attempt has been made to provide a logical foundation on which to base the design of this turbopump unit in such a manner that the weight of the complete power plant will be the minimum. Rigorous analysis is impossible because of the factors of design technique which enter into any weight assumption. Furthermore, comparison and extension of the data to existing power plants are impossible because of the classified nature of the information. The results as presented, however, clearly show effect of the principal variables both in turbine and pump design, and use of equations developed provide the engineer with a method of studying optimum turbopump design for any rocket application.

Description of Systems

Fig. 1 shows a simplified schematic diagram of a chemical turbine power plant (3, 4, 5).[1] The main function of the turbopump is to supply both fuel and oxidizer to the thrust chamber at a predetermined pressure. More

[1] Numbers in parentheses refer to the Bibliography at the end of this paper.

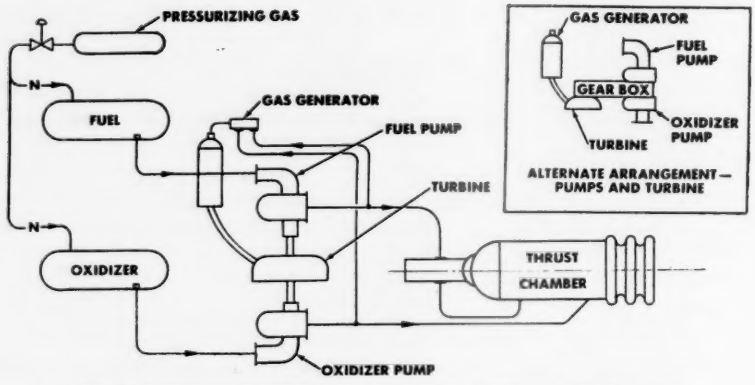

FIG. 1 SIMPLIFIED FLOW DIAGRAM OF CHEMICAL TURBINE POWER PLANT

complicated systems involving the control of propellant flow are used for variable thrust applications. However, for the purpose of this analysis, the simplified system as shown in Fig. 1 is assumed. Such a system is usually in hydraulic balance to such an extent that metering is not required. The mixture ratio (the ratio of weight rates of flow of fuel and oxidizer) is held constant over the operating range by means of matching pump-head characteristics or orifice restrictions.

The application of the rocket power plant falls into two general classifications: (1) An auxiliary power plant such as is used for assist take-off; or (2) a prime power plant such as would be used in a rocket-powered missile. The arrangement of the system in specific installations may have several variations in that certain components may be externally mounted and droppable from the vehicle. Such variations are not considered. The analyses included herein are based on power plants which are completely contained within the vehicle.

In the case of the auxiliary or assistant take-off power plant, it is immediately evident that the fixed or empty weight of the power plant is of prime importance, since its propellant load is consumed or expended early in the flight of the vehicle. It follows axiomatically that this expendable weight of propellant, which is principally determined by the efficiency of the propellant combination, is of secondary importance as compared to items of weight which must be carried during the entire flight. In the case of the prime power plant, a governing parameter is impulse/weight ratio, defined as the total impulse (I_t) divided by the dry weight plus the propellant weight. In this case, the weight of the propellants, as determined by the performance or specific impulse (I_{sp}) of the propellants, is of the same order as the fixed weight of the components, since it is desirable to have the numerical value of the parameter as high as possible.

Other considerations which must be reckoned with in the design of either class of installation are safety and complexity and their relative influence on fixed weight. Obviously, these are requirements of specific applications and only general statements can be made concerning their significance. In piloted vehicles, safety is of great importance and in its interest additions in fixed weight are certainly allowable. In missile applications where danger to personnel is of lesser importance and where operation is sometimes vitally important regardless of minor malfunctioning, safety devices must be held to a minimum. The advantages gained by increased complexity are usually accompanied by increased manufacturing costs against which any gain has to be balanced. It should be noted, however, that in the case of assist take-off power plants, a decrease in complexity may be logically considered if it involves no increase in the fixed weight of the unit. This point is further emphasized when the design of the turbine itself is considered.

Turbine and Gas Generator

Previous study has established the superiority of the impulse-type wheel for the chemical-type rocket turbines from the standpoint of both efficiency and simplicity. The addition of a second velocity stage improves the efficiency based on fuel consumption, but it increases the fixed weight of the turbine itself, as well as its complexity. The efficiency of the turbine is important only in the case of the prime power plant, since efficiency is reflected to a first approximation in the weight of propellants used to generate the turbine gases. This weight, as previously explained, is of secondary importance in the auxiliary power-plant application.

The consideration of efficiency, however, is important in establishing the type of turbopump for the given application. Since the efficiency of the impulse-type turbine is related principally to its velocity ratio (u/c), it is important for a design in which efficiency is significant to operate close to the optimum value of this parameter. Because the absolute value of c, the velocity of the gas entering the turbine, is relatively high (2000 fps), it is generally necessary to design for operation at the highest possible shaft speed with the minimum allowable wheel diameter. The decision as to whether or not to use a second velocity stage must be dependent on an individual weight analysis of its merits.

In general, it will be found that a turbine designed on the basis of optimum u/c would have to operate at a shaft speed considerably greater than is permitted by the best available design of centrifugal pump for the application. However, in an assist take-off application it is not unusual to base the turbine design speed on the optimum pump speed, allowing the pumps and turbine to operate on a single shaft. Although the weight of the gas-generating propellants is thus increased, the increase represents, as previously noted, expendable weight, and it is of secondary importance.

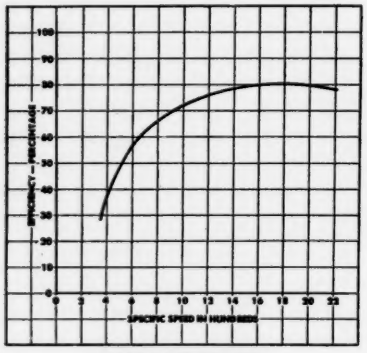

FIG. 2 EFFICIENCY VERSUS SPECIFIC SPEED FOR AEROJET IMPELLER STYLES (BASED ON DESIGNS AVAILABLE AT AEROJET; REFERENCE: AEC REPORT NO. 228)

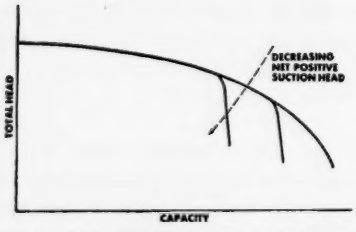

FIG. 3 PERFORMANCE—TYPICAL CENTRIFUGAL PUMP

Propellant Pumps

It is more difficult to establish the operating characteristics of a pump than those of a turbine because of the greater number of variables involved (1, 2). In order to explain clearly the design parameters, the following brief discussion of pump characteristics is presented.

The detail design of centrifugal pumps is well covered in the literature in so far as head, capacity, speed, and efficiency relationships are concerned. Briefly, specific speed is the designer's most widely used parameter.

$$N_s = \frac{NQ^{1/2}}{H^{3/4}}$$

where

N_s = specific speed
N = speed of pump, rpm
Q = capacity of pump, gpm
H = total head of pump, ft

It is possible to relate pump efficiency to the specific-speed parameter, as shown in Fig. 2. This curve may be modified and improved by specific cases; however, it is believed to represent attainable values with the design techniques now available.

The use of standard pump-design techniques as discussed above is based upon the assumption that the pump operates under noncavitating conditions, or in other words, sufficient pressure is applied to the suction side of the pump to prevent local pressures from dropping to the vapor pressure of the pumped fluid at points of high velocity. With the exception of boiler-feed pumps, this condition is not usually critical in commercial applications. In all rocket pumping plants, however, it becomes a major problem, and is therefore considered in greater detail in this paper in order that the effects of cavitation can be fully appreciated.

In radial and in many mixed-flow types of centrifugal pumps, cavitation occurs as shown in Fig. 3. For decreasing values of net positive suction head, flow remains constant and total head decreases rapidly. Depending on the installation, this condition may not be stable, and slight variations

in speed or flow demands will cause the total head developed to fall to zero. This phenomenon is known as "vapor-locking," and is especially serious in a rocket system because it completely cuts off one of the reactants, thus creating a condition under which a destructive explosion might occur. Furthermore, the abrupt drop in total head to a value less than zero under cavitating conditions can have a serious effect on mixture ratio in a hydraulically balanced system.

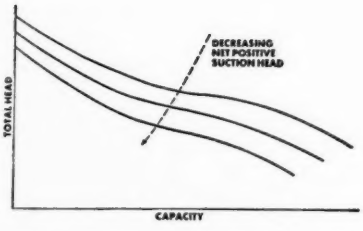

FIG. 4 PERFORMANCE—TYPICAL AXIAL-FLOW PUMP

In mixed-flow type pumps of higher specific speeds and in straight axial-flow pumps, cavitation occurs as shown in Fig. 4. This condition is stable and fluctuations in either speed or flow will not cause cutoff or vapor-locking of the unit.

The suction pressure required to operate any type of centrifugal pump is described by either one of two common parameters. Each makes use of the term *NPSH* (net positive suction head) relating to the required head above the vapor pressure of the fluid to produce noncavitating operation. The first, known as the sigma (σ) parameter, is given as follows:

$$\sigma = \frac{NPSH}{H} = \phi(N_s)$$

where

$NPSH$ = net positive suction head
H = total head
N_s = specific speed

For an established design range, the function of σ vs. N_s is a straight line on log-log paper, and σ is a function of the 4/3 power of N_s. Since N_s contains the term H, rearrangement of the above equations can be accomplished and it can be shown that:

$$NPSH^{3/4} = \phi(Q^{1/2}N)$$

This is the basis of the second parameter, which is known as "suction specific speed," and is represented as follows:

$$N_{ss} = \frac{NQ^{1/2}}{(NPSH)^{3/4}}$$

where

N_{ss} = suction specific speed
N = speed, rpm
Q = capacity, gpm
$(NPSH)$ = net positive suction head, ft

Further examination of this parameter is of interest since it becomes desirable to increase the operating value as high as possible. In attempt-

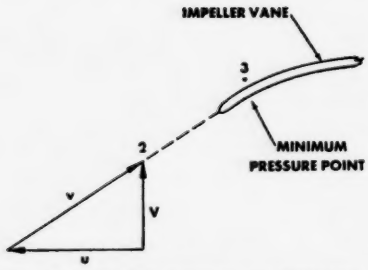

FIG. 5 VELOCITY DIAGRAM AT IMPELLER VANE ENTRANCE
(NOTE: VAPOR PRESSURE EXISTS AT POINT 3 AT THE START OF CAVITATION)

ing to increase this factor, it is necessary to have an understanding of the specific design features of a centrifugal pump affecting this factor. For this purpose, let us consider the eye of a centrifugal pump, as in Fig. 5. Cavitation will occur at the outside diameter, at a point on the vane where the pressure is a minimum and the velocity a maximum. At incipient cavitation, the local static pressure will be equal to the fluid-vapor pressure, and the static pressure just upstream from the vane can be calculated as follows:

$$h_{s_2} = k\frac{v^2}{2g} + h_v \quad \ldots\ldots [1]$$

$(1 + k)$ is defined as the ratio $(v_3/v)^2$, where v is the relative velocity of the fluid entering the vane, and v_3 is the relative velocity of the fluid at the minimum pressure point of the vane. (See Fig. 5.) The total pressure at the pump inlet is then

$$h_{t_1} = h_{s_2} + \frac{V^2}{2g} = k\frac{v^2}{2g} + h_v + \frac{V^2}{2g}, \text{ but } v^2 = V^2 + u^2 \quad \ldots\ldots [2]$$

so

$$h_{t_1} = h_v + k\left(\frac{V^2}{2g} + \frac{u^2}{2g}\right) + \frac{V^2}{2g} \quad \ldots\ldots [3]$$

and the net positive suction head is

$$h_{sv} = h_{t_1} - h_v = (1 + k)\frac{V^2}{2g} + k\frac{u^2}{2g} \quad \ldots\ldots [4]$$

For pumps in which the vane tip extends to the pump eye, both V and u are functions of diameter and

$$h_{sv} = C_1(1 + k)Q^2\frac{1}{d^4} + C_2kN^2d^2 \quad \ldots\ldots [5]$$

The diameter leading to the lowest value of h_{sv} may be found as follows:

$$\left(\frac{\partial h_{sv}}{\partial d}\right) = -4C_1(1 + k)Q^2\frac{1}{d^5} + 2C_2kN^2d = 0 \quad \ldots\ldots [6]$$

from which

$$d_0^3 = \left(\frac{2C_1}{C_2}\right)^{1/3}\left(\frac{1 + k}{k}\right)^{1/3}\frac{Q^{2/3}}{N^{2/3}} \quad \ldots\ldots [7]$$

Substituting d_0 into the expression for h_{sv} we find that

$$(h_{sv})_c = AQ^{2/3}N^{4/3} \quad \text{.....[8]}$$

where A = a function of k only.

The corresponding optimum suction specific speed is

$$(N_{ss})_0 = \frac{N\sqrt{Q}}{(h_{sv})_0^{3/4}} = \frac{N\sqrt{Q}}{(AQ^{2/3}N^{4/3})^{3/4}} = \frac{1}{A^{3/4}}$$

or

$$(N_{ss})_0 = \frac{5150}{(1+k)^{1/4}k^{1/3}} \quad \text{.....[9]}$$

This indicates that, for a properly chosen inlet-eye diameter, the suction specific speed is only a function of k, which is a property of the impeller vanes. For an infinitely thin vane, k approaches zero at the design angle, increasing very rapidly, however, as the angle of attack changes with changing flow rate. For a vane which allows a certain amount of latitude for inlet angles and which is thick enough for structural purposes, k = 0.15, which corresponds to an optimum $(N_{ss})_0$ = 13,000. This is the optimum which can be reached without any cavitation taking place in the pump. If the operating N_{ss} is raised beyond this point, either by lowering h_{sv} or by raising N, cavitation will take place. This may not be objectionable at first. The cavitating region will extend outward along the vane but the required discharge will still be able to pass through the restricted flow area. If the area is restricted too much by the cavitating region, the flow quantity will be reduced. Up to this point, the operation may still be useful for rocket power-plant operation.

Both Stepanoff (1) and Wislicenus (2) in their recent treatise on pumps recommend that N_{ss} values be held at 8000 to 10,000 maximum for normal design. The effect of cavitation, aside from its influence on pump performance, as previously explained, is local deterioration in a form similar to severe pitting on the inlet part of the vanes of the pump impeller. If this pitting is allowed to progress sufficiently, structural failure will occur. Although this effect is of major importance in ordinary commercial pumps, it may be disregarded in rocket systems for the following reasons: First, the life of a rocket pumping unit is very short; second, the condition of maximum *NPSH* requirement exists only at the extreme high-temperature condition which likewise takes up only a small percentage of the turbopump's operating life. At normal conditions (liquid temperatures below 100 F), the increment of suction pressure equivalent to the difference in the vapor pressures between the high- and normal-temperature conditions is reflected as additional suction pressure above the amount required.

From the standpoint of turbopump design, maximum attainable values of N are desirable to permit operation of the pump at a shaft speed comparable to that of the turbine and to keep the pump weight and space requirements at a minimum. Moreover, the pump weight (assuming constant head and capacity) will vary as an inverse power of the speed. To

take advantage of the increase in speed, it is necessary to maintain a comparable value of *NPSH* at the suction of the pumps. An increase in *NPSH* would in turn mean an increase in tank pressure, which would necessitate greater tank weights and, in some instances, added equipment.

A study of the N_{ss} parameter shows immediately that the above-noted condition of increasing N and decreasing *NPSH* can be attained only if N_{ss} can be increased. As a consequence, considerable effort is directed toward this end. The effect of operation at above-normal values of N_{ss} and its relation to rocket pumps is worthy of note.

It is also of interest to consider the case in which the design speed changes, but in which *NPSH* cannot be maintained. Instead, it may be assumed that the suction specific speed, N_{ss}, which corresponds to any pumps of similar eye design, remains constant. In that case, the increase in design speed will cause a decrease in pump and turbine weight, but on the other hand, the pumps will require a higher *NPSH*, which requires an increase in tank weight. An optimum speed should exist in this case, and its analysis is presented later in this discussion.

Advances have been made in the mechanical and hydraulic design of pumps in the past few years with respect to increasing the operating N_{ss} above the critical value (13,000). A typical method is the use of an axial-flow inducer on the suction side of the pump. The inducer may be either a separate stage with stay vanes and diffuser, or it may be located directly in the eye of the main pump impeller. Under extreme operating conditions (high N_{ss}), the inducer cavitates, and some loss in efficiency and head at constant flow is experienced. The loss in total head of the inducer-impeller combination affects the mixture ratio and thrust level control; however, it is believed that major difficulties in this respect can be avoided by careful design. The extent to which the degree of cavitation is allowable in this configuration depends on the effects mentioned and on the detail hydraulic design as affecting the life of the pump. The over-all advantage is more clearly visualized in examination of the equations developed in the following section.

Optimum Design Considerations

For the sake of simplicity, the arrangement of the complete power plant is assumed to be similar to that shown in Fig. 1, with a turbine operating at the same speed and on the same shaft as the pumps. This system lends itself to an approximate analysis, the results of which can be used as a guide to the importance of all the design variables. A rigorous treatment of the problem is of course impossible, since design technique plays such an important role in determining the individual component weights.

With these thoughts in mind, consider the components of fixed weight

affected by the operating conditions of the turbopump. First, the weight of the turbopump itself varies as its design speed changes; second, the propellant-tank weight varies as more or less metal must be used to counterbalance the change in pressurization requirements occasioned by the value of *NPSH* varying with the speed of the turbopump. The working pressure of the tank for a given set of conditions will be established by a number of factors, including vapor pressure of the fluid, losses in the suction lines to the pumps, safety vent setting, and the *NPSH* of the pumps. For a given thrust rating, however, the only variable is the *NPSH*. For the purpose of simplifying the development of equations to include only the principal variables, the following general assumptions are made:

1 The fixed weight of the propellant tanks and pressurizing system varies directly with the total impulse I_t, and the maximum working pressure as affected by changes in *NPSH*.

2 Changes in valve, line, and gas-generator weights at constant thrust within the range considered are not significant.

3 The turbopump total weight varies inversely as the square of the design speed. This is considered conservative, as the pumps vary approximately inversely as the square, and the turbine inversely as the third power of speed for constant head-capacity conditions and constant velocity ratio (u/c).

4 The *NPSH* of the oxidizer pump governs the amount of pressurization required by the propellant tanks. This condition is frequently found in operating power plants.

On the basis of these assumptions, an equation can be set up for the analysis of the effect of the variables I_t, N, and N_{sv} on $\overline{W}_t$, the weight of fixed components for a single thrust rating. This equation takes the form:

$$\bar{W}_t = k_1 N^{-2} + k_2 I_t (NPSH - p_n) + W_t + C \quad [10]$$

where

$\bar{W}_t$ = total weight of fixed components, lb
k_1, k_2 = constants
N = shaft speed, rpm
I_t = total impulse, lb/sec
$NPSH$ = net positive suction head, lb per sq in.
p_n = design *NPSH*, lb per sq in.
W_t = total weight of tank shell for design *NPSH* of p_n, lb
C = constant

The first term, $k_1 N^{-2}$, represents the turbopump weight; the second term, $k_2 I_t (NPSH - p_n)$, the change in weight of the propellant tank; the third term, W_t, the tank weight at a design *NPSH* of p_n; and the fourth term, C, the weight of all other fixed components such as structure, thrust chambers, valves, etc., not affected by the turbopump design. Substituting for *NPSH* in terms of N, F, and N_{sv}:

$$\bar{W}_t = k_1 N^{-2} + k_2 I_t \left(\frac{N^{4/3} F^{2/3} k_3 - p_n}{N_{sv}^{4/3}} \right) + W_t + C \quad [11]$$

Differentiating with respect to N, and setting $\frac{\delta \bar{W}_t}{\delta N} = 0$ to determine optimum weight and speed relationships:

$$N_{(\text{optimum})} = 1.13 \left(\frac{k_1}{k_2 k_3}\right)^{0.3} N_{sv}^{0.4} F^{-0.2} I_t^{-0.3} \quad [12]$$

or

$$N_{(\text{optimum})} = k' N_{sv}^{0.4} F^{-0.2} I_t^{-0.3} \quad [13]$$

The thrust F does have an effect on the pump weight as well as on the fixed weight, represented by C. This effect was not included explicitly in Equation [11]. Detailed examination indicates, however, that the weight of the turbopump is affected little at a given speed and discharge pressure by small changes in capacity or, conversely, in thrust. Thus, by substituting in Equation [13] F_t for I_t, the impulse, a still more general equation may be written, which may be used as a first approximation for determination of optimum N for each given thrust F as well as for each value of the other variables, t and N_{sv}.

$$N_{(\text{optimum})} = k' N_{sv}^{0.4} F^{-0.5} t^{-0.3} \quad [14]$$

A survey of Equations [12] and [14] from the standpoint of accuracy is also interesting. Accuracy will be determined by proper selection of the constants k_1, k_2, and k_3. Since they all enter the equation either in the numerator or the denominator and to the 0.3 power, it is evident that the effect of error in the individual constants is reduced.

Examining the individual constants, k_1 is proportional to the turbopump weight at any design speed. Reduction of the value of this constant depends on the ingenuity of the designer and the further development of design techniques. The constant k_2 is approximately inversely proportional to the allowable stress in the propellant tanks and to the density impulse of the propellant. To include more independent variables in the over-all analysis, the expression could be rewritten as follows:

$$k_2 = \frac{k_2'}{I_d S_w k_4}$$

where

k_2' = constant
I_d = density impulse of propellant
S_w = allowable working stress of tank material
k_4 = material constant: $k_4 = 1$ for steel, $k_4 = 3$ for aluminum

Since I_d is not considered a design parameter, reduction of the absolute value of k_2 in the interest of reducing total weight can come about only as the development of materials makes possible an increase in S_w, the allowable working stress of the tank. It should be noted that reduction of the absolute values of both k_1 and k_2 are dependent on development and design techniques. In view of this, together with the fact that maximum

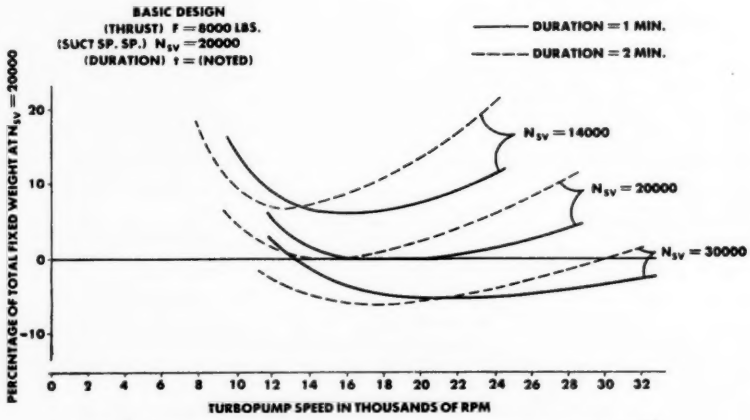
BASIC DESIGN
(THRUST) F = 8000 LBS.
(SUCT SP. SP.) N_{sv} = 20000
(DURATION) t = (NOTED)
DURATION = 1 MIN.
DURATION = 2 MIN.
N_{sv} = 14000
N_{sv} = 20000
N_{sv} = 30000
PERCENTAGE OF TOTAL FIXED WEIGHT AT N_{sv} = 20000
20
10
0
-10
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
TURBOPUMP SPEED IN THOUSANDS OF RPM

FIG. 6 CURVES SHOWING EFFECT OF VARYING DESIGN PARAMETER N_{ss}

changes possible are of about the same order, it is believed that the factor $(k_1/k_2)^{0.3}$ appearing in Equation [12] should stay approximately constant if power plants of a reasonably advanced design are considered.

The absolute value of k_3 is a function of mixture ratio, propellant density, and specific impulse, all of which are instrumental in determining the volume flow rate of the propellant in the power plant. If reasonable allowances are made for variations in specific impulse and design at various mixture ratios, the effect of variation of k_3 on optimum operating speed for a given propellant combination should not exceed $\pm 2^1/_2$ per cent.

For an original design, the evaluation of constants in Equation [10] above is difficult. However, the use of data from a completed design is a simple matter, and serves to illustrate several interesting points. Because complete data on the characteristics of a power plant are of a classified nature, only the results of a study can be given at this time. A power plant, using acid as the oxidizer, of 8000-lb thrust, 60-sec duration, and with a design suction specific speed (N_{ss}) of 20,000 was considered, and the constants calculated as follows:

$$k_1 = 98.0 \times 10^6$$
$$k_2 = 5.55 \times 10^{-6}$$
$$k_3 = 4.62 \times 10^{-2}$$
$$k' = 1.08 \times 10^5$$

The results of the calculations are shown in Figs. 6 and 7, and clearly illustrate the effect of such variables as suction specific speed, pump and turbine speed, and duration.

It is interesting to note from Fig. 6 that small variations in the design speed of the turbine and in rated duration are not particularly significant. However, the significance of suction specific speed is shown clearly in

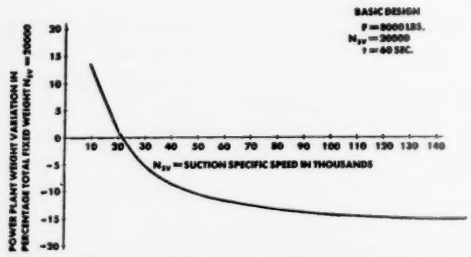

FIG. 7 CURVE SHOWING TOTAL POWER-PLANT WEIGHT VARIATION AS A FUNCTION OF N_{sv}

Fig. 7. Improvements of this parameter from 10,000 to 30,000 result in a decrease in total power-plant weight of approximately 20 per cent.

Conclusion

In conclusion, it may be pointed out how the foregoing analysis may be extended if more complicated arrangements than the single-shaft turbopump are to be studied. If, for example, a gear reducer is to be used so that the turbine may operate at the highest speed consistent with the strength of the wheel, the optimum pump speed may be found as follows: The total weight of the installation is now

$$W_t = k_1^1 N^{-3} + k_2 I_t (NPSH - p_a) + W_t + C_1$$

where all the symbols have the same meaning as before, except that k_1^1 refers to the pumps only, and C_1 includes the gear reducer and the turbine wheel. N is equal to the pump speed and k_1^1 is, of course, smaller than k_1 for any two comparable designs. Differentiating this equation in respect to N_1, an expression for the optimum pump speed is obtained which is entirely analogous to Equation [12] except that k_1 is now replaced by k_1^1. Since $k_1^1 < k_1$, this means that the optimum pump speed for the geared system would be lower than the speed for the single-shaft system. For a typical case, the ratio (k_1^1/k_1) may be 0.5, which would mean a difference of about 20 per cent for the two speeds.

Similar analysis may be made for other systems, and if sufficiently accurate information is available, refinements in the above analyses may be warranted. For example, the effect of thrust on pump weight and the effect of speed ratio on gear weight, etc., may be taken into account. In all cases, however, it will be possible to determine an optimum speed, and it is believed that the engineer should give careful consideration to the existence of this optimum in the design of turbopumps.

The author wishes to express his appreciation to Prof. R. G. Folsom, University of California at Berkeley, and Assoc. Prof. Aladar Hollander, California Institute of Technology, consultants to the Aerojet Engineering Corporation in the field of hydrodynamics, for their valuable assistance in the preparation of material presented in this paper.

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THE FORRESTAL JET RESEARCH CENTER

PRINCETON University has bought an 800-acre tract adjoining its campus to be used for a new research center on jet propulsion and related sciences. The center, according to *The New York Times*, will be named for the late James Forrestal, the nation's first Secretary of Defense, who was a member of Princeton's class of 1915.

This memorial to Mr. Forrestal will be established on property just acquired by the university from the Rockefeller Institute for Medical Research for "about $1,500,000," Dr. Harold W. Dodds, President of the university said.

The property already has two large laboratories and several smaller buildings, which were used by the institute's department of animal and plant pathology before its recent move to New York City. Thus the new center will be able to start work within a few months, after various research equipment is transferred from the campus. With the installation of this equipment, the center will have a plant that could not be reproduced now for less than $3,000,000, it was said. In a statement explaining the university trustees' decision to spend the $1,500,000, which they hope to get back through a special fund drive, Dr. Dodds said:

"Princeton possesses exceptional faculty assets for a major defense contribution, but we have felt that we could realize upon these assets only if major steps could be taken to integrate our scientific research and teaching and greatly expand the work space available for it."

With the acquisition of the new plant and property on the Brunswick Pike adjoining the university's campus on the east bank of Lake Carnegie, this integration and expansion becomes possible, he added.

The new James Forrestal Research Center will draw its faculty from the university's departments of aeronautical engineering, chemistry, chemical engineering, physics, mathematics, and mechanical engineering.

The several projects related to the aeronautical sciences on which members of these departments have been working—studies in jet propulsion, heat transfer, high-temperature metallurgy, and related areas—will all be carried on at the new center. Work in these fields has been proceeding largely under the sponsorship of various Government agencies, principally the research arms of the Navy and Air Force.

BALLISTICS PROGRAM AT OHIO STATE UNIVERSITY

By C. J. Peirce[1] and W. P. Berggren[2]

Teaching and research programs in ballistics at Ohio State University are described briefly. This work is thought to be of interest to ballisticians, aeronautical engineers, and others working in high-speed phenomena. Development work on the liquid-hydrogen–liquid-oxygen motor is of special importance in connection with the prospects of missile flights over long distances and at great altitudes.

THE PROGRAM in ballistics at Ohio State University consists of a graduate curriculum and several extensive research programs conducted on the University campus at Columbus. The instructional phase of the program was first instituted at the OSU-Wright Field Graduate Center in the spring of 1948 when the first of a series of courses in exterior ballistics was offered. The research work on the campus covers fundamental development work on high-impulse rocket fuels, investigation of radiation patterns from missile antennae, and development of photogrammetric procedures for determination of orientation of missiles in actual flight. Research contracts for all work are under the administration of the OSU Research Foundation.

Wright Field Graduate Center

To encourage graduate study and research in engineering, physics, mathematics, chemistry, physiology, economics, and related fields, the Ohio State University in 1946 instituted a Graduate Center at Wright-Patterson Field, Dayton, Ohio, in co-operation with the Air Materiel Command and the Air Force Institute of Technology. The institution and development of this Center were carried out under the terms of a contract between the Air Materiel Command and the University. The contract has been in force since 1946. Present enrollment is approximately 350.[3]

Exterior Ballistics Program at Wright Field

As part of the graduate program in aeronautical engineering being offered at Wright Field, a series of five courses in exterior ballistics was made

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[3] "OSU-Wright-Patterson Graduate Center," by S. M. Marco and C. J. Peirce, *Journal of Engineering Education*, Nov. 1949, pp. 187–191.

available beginning with spring quarter of 1948. The first three of these courses were concerned with the ballistics of shells and rockets with particular emphasis on rockets fired from aircraft. The last two courses were concerned with the exterior ballistics of missiles and considered some of the problems encountered in satellite and escape missiles. By arrangement with the Security Personnel, special clearance was obtained to present material of a confidential nature in the later work. The courses mentioned above carried graduate credit and were taken by men working for the master degree in aeronautical engineering or mechanical engineering.

A list of topics covered in the first three courses follows: History of ballistics; trajectory in a vacuum; force and moment system on projectiles; stability of the projectile; retardation functions; numerical integration of the trajectory equations; bomb ballistics; force system on a rocket; equations of motion of the rocket; solutions of the equations of motion during launching and burning and after burning; and mathematical properties of the rocket functions.

Mimeographed lecture notes for the above courses were prepared using Aberdeen Proving Ground reports and various texts on shell and rocket ballistics. The rocket treatment was based largely on the "Mathematical Theory of Rocket Flight" by Rosser, Newton, and Gross.[4]

The remaining two courses, which were concerned with missile ballistics, covered such topics as: vector calculus; Lagrange's equations; Corioli acceleration; motion of a missile on a rotating earth; escape missiles; satellite missiles; rocket-powered aircraft; and performance of the V-2 and of sounding rockets.

Reports of the NACA and of Aberdeen were used for much of this material. The recent text "Ballistics of the Future" by Kooy and Uytenbogaart[5] was useful in connection with this work.

In planning the subject matter for the above courses, attention was given to items which would be of use to American Materiel Command personnel registered in this program, and an emphasis was placed on providing a sound fundamental training in ballistics, mathematics, and physics, rather than a specialized treatment of detailed trajectory considerations. Discussions which were held with R. H. Kent and others at Aberdeen and with Dr. C. C. Bramble of the Navy Proving Ground at Dahlgren were helpful in the organization of this program of instruction.

In addition to the ballistics courses described, instruction was offered in the chemistry of explosives and high-altitude meteorology to smaller groups who were interested in these subjects. The program of basic courses available in mathematics, physics, and other related subjects is described in the paper by S. M. Marco and C. J. Peirce.

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[4] Published 1947, by McGraw-Hill Book Company, Inc., New York, N. Y.
[5] Published 1948, by McGraw-Hill Book Company, Inc., New York, N. Y.

Rocket-Propulsion Courses at Wright Field

During the academic year 1949–1950 a course sequence in rocket-propulsion systems was added to the Wright Field program. An introductory course in principles of rocket propulsion was first offered, concurrently with a course in thermodynamics of rocket power plants. The latter course consisted of the following topics: Review of rocket power-plant components and terminology; review of pertinent principles of thermodynamics and fluid mechanics; the combustion process in rockets; computation of the performance of rocket-propellant systems; determination of the effect of nozzle expansion on rocket performance; and heat transfer in rocket motors.

The current program of instruction includes a course in rocket-propellant flow systems, covering the following items: Physical and chemical properties of rocket propellants; pressure and flow regulation; pumping of rocket propellants; and power-plant stability and control.

The concluding course of the propulsion sequence will deal with over-all design and application of rocket power plants, with special reference to the interrelation between power-plant design and the nature of the propelled vehicle; piloted aircraft; short or long-range missiles; and multistage rockets. Sample comparisons of the applicability of various propellant combinations to given tasks will be made.

Teaching Program on OSU Campus

A somewhat modified series of courses with emphasis on the ballistics of rockets has been offered on the OSU campus at Columbus. A summary course in rocket ballistics was offered in 1949 for engineers of the Curtiss Wright plant and the first series of three courses is currently being taken by a group of aeronautical-engineering and physics students. The campus courses cover ballistics fundamentals and the various aspects of rockets which can be treated without the introduction of classified material. A brief treatment of escape rockets and of multistep rockets is also included.

Several graduate students are engaged in the preparation of masters theses on ballistics of rockets. An introductory course in rocket motors is presently available. It is expected that the more detailed courses in this subject, which are presently being taught at Wright Field, will be offered on the campus in the near future.

Liquid-Rocket-Motor Development Work

The OSU Cryogenic Laboratory, under direction of Dr. H. L. Johnston, has been engaged in the investigation of liquid hydrogen as a rocket fuel

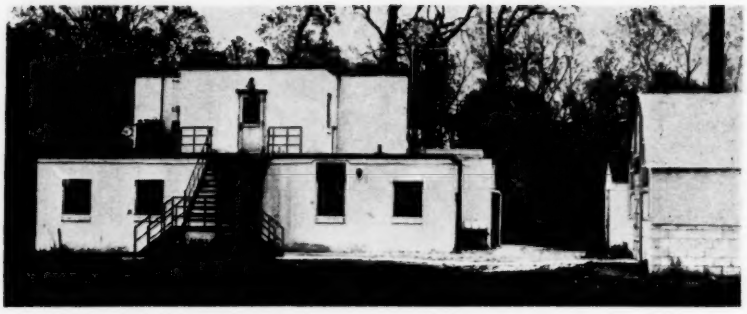

FIG. 1 FRONT VIEW OF ROCKET-TEST LABORATORY AT OHIO STATE UNIVERSITY

for the past several years. This investigation has included the production and handling of liquid hydrogen, measurement of physical properties of liquid hydrogen, and the behavior of metals at temperatures as low as the boiling point of hydrogen (−423 F). Current work also includes determination of pressure-volume-temperature relationships and thermodynamic properties of hydrogen between its boiling point and 80 F.

The OSU rocket-motor and pump-research program, under auspices of the Air Materiel Command, has been centered around studies of the performance and heat-transfer characteristics of propulsion units operating on the hydrogen-oxygen propellant combination.

The extremely low temperature, low density, and high rate of thermal expansion of liquid hydrogen result in pumping and handling problems not encountered with more common fluids. Commendable progress is being made in the principal problems associated with handling and testing.

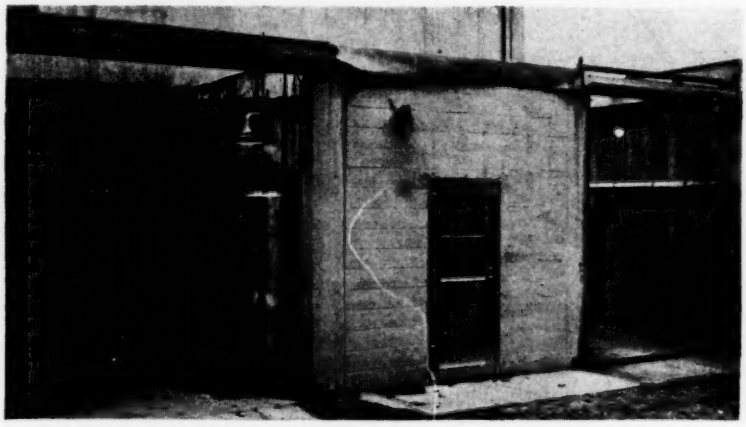

FIG. 2 ROCKET-TEST CELLS

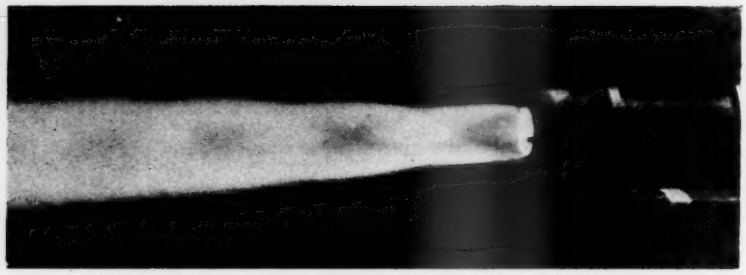

FIG. 3 LIQUID HYDROGEN-OXYGEN MOTOR IN OPERATION

Figs. 1 and 2 are front and rear views of the rocket-test laboratory. Fig. 3 shows a hydrogen-oxygen rocket motor in operation.

The OSU Antenna Laboratory, which is under the direction of E. E. Dreese and V. H. Rumsey of the department of electrical engineering, has been engaged for several years in various aspects of antenna research and design connected with guided missiles. Part of the work has been concerned with the research and study of impedance parameters and radiation characteristics of antenna types which would be applicable to radar missile application. Some of the problems have centered around design criteria for obtaining special radiation characteristics from flush-mounted radiating elements, as well as control of radiation polarization. This work is being carried out under contract for the Air Materiel Command.

Activity of the Mapping and Charting Laboratory

The Mapping and Charting Research Laboratory of the Ohio State University Research Foundation is under the direction of G. H. Harding. This laboratory was given the assignment, as a part of its Air Force research contracts, of attempting to determine the aspect of a V-2 guided missile during an actual flight. This was accomplished by using photogrammetric computational procedures and 35-mm photographs taken from the missile itself. The aspect, which includes azimuth, inclination, and rotation, was determined for each second of flight.

Following completion of the computational work, a moving picture was produced by the OSU photographic department, using a model rocket which exactly reproduced the movement and flight of the rocket from the time of firing to the point where the recording cameras were ejected from the missile by explosive charges several seconds after the missile had begun its fall from the highest altitude reached.

The missile-model-flight-film projection time was exactly synchronized with the actual flight time. This permits the viewer of the film to see every motion of the missile with the same timing as it occurred in the actual flight. To the best of our knowledge, this is the first time that guided-missile flight has been accurately simulated in the laboratory.

What to Expect in Atomic Energy Rocket Reviewed at ARS New York Section Meeting

BECAUSE of the enormous energy obtainable from very small amounts of fuel, nuclear reactions might appear to open up tremendous possibilities in rocketry. A critical study of nuclear-energy literature reveals, however, that the day of the chemically fueled rocket may be far from over. Severe limitations in the current state of the engineering arts, particularly in heat transfer and high-temperature metallurgy, justify pessimism in the practicability of nuclear rockets with spectacular performances.

This was the gist of a talk delivered before a capacity audience by C. W. Chillson, consulting engineer, Propeller Division, Curtiss-Wright Corporation, Caldwell, N. J., at a regular meeting of the New York Section of the American Rocket Society held at the Engineering Societies Building, New York, N. Y., Jan. 19, 1951. The subject of his talk was "Atomic Energy Rocket—Why, How, and If."

He discussed the "why" from two standpoints. The first referred to the goals which we may wish to achieve. Increasingly difficult are (1) long-range missiles for transportation from one part of the world to another; (2) establishment of space stations occupying satellite orbits and revolving about the earth; and (3) complete escape from the gravitational field of the earth for interplanetary or interstellar travel. The second referred to the limitations of chemical rocket which he established with the help of illustrations which related the propellant loading ratio (propellant weight/total missile weight), and chamber temperatures to a performance parameter, the missile velocity at the moment when all propellants are expended. These showed that even an optimistic oxygen-hydrogen propellant rocket in which $^9/_{10}$ of the starting weight is propellants, might be barely possible to establish a satellite space station. By the employment of multiple-step chemical rockets, however, it should be possible to theoretically reach any of the goals enumerated, he said.

In pursuing the "how" theme, Mr. Chillson first commented briefly on the two basic types of nuclear reactions, fusion and fission, and concluded that the fusion reaction, while more energetic, takes place only under conditions of temperature and pressure which cannot by any means known today be physically contained and made continuous. In examining various means of using the nuclear fission reaction, which he felt might be fairly readily adaptable to rockets, he discarded fission fragment rockets, radiation rockets, and charged particle rockets, because each of these types for one or more reasons does not appear practical on the basis of present knowledge.

He examined in detail several versions of a fourth type, the "neutral particle rocket," in which a working fluid such as hydrogen, ammonia, methane, etc., is heated by a nuclear reaction. Because of its low molecular weight, hydrogen was felt to be a good selection.

ACTIVE MEMBERS OF THE ARS NEW YORK SECTION

(Left to right: Paul F. Winternitz, director of laboratories, Reaction Motors, Inc.; C. W. Chillson, consulting engineer, Curtiss-Wright Corporation; Frank A. Coss, Reaction Motors, Inc.)

Neutral-particle-rocket schemes fall into two general classifications. The first involves heat transfer from an atomic pile made in the form of a heat exchanger to the working fluid. The performance of this type, he said, is limited by the allowable operating temperature of possible pile materials. Using tungsten (melting at 6550 R) the working fluid could be heated to 5000 R, which corresponds to temperatures currently being handled in chemical rockets. At this temperature, rocket-motor performance, in terms of exhaust velocity or specific impulse, is less than three times that achievable with chemical propellants. In such a nuclear rocket (in which heat transfer is from a solid to a gas) performance levels much greater would be unlikely, since improvements in the temperature resistance of engineering materials could not be expected to be by order of magnitude but only in degree.

The second main classification involves the direct heating of the working fluid by fission fragments, radiations, etc., from the nuclear reaction. This method should permit substantially higher operating temperatures and hence higher performance, since with this type it is only necessary to develop means of containing the gases, not of heating them by metal surfaces. He stated, however, that this latter system is subject to many questions from a nuclear physics standpoint and may or may not be feasible.

Mr. Chillson felt that nuclear rockets should be developed only if they give promise of either achieving spectacular results impossible in chemical rockets, which he felt to be unlikely on the basis of present knowledge, or if the problems of ultimately developing atomic rockets are found to be less difficult of solution than chemical rockets of equal performance.

At the close of the meeting Mr. Chillson gave the ARS members a useful bibliography of unclassified publications pertinent to atomic-energy rockets which he had used in the preparation of his talk.

New Officers

Three new members have been elected to the New York Section Board of Directors. They are: Frank A. Coss, project engineer, Reaction Motors, Inc.; James R. Randolph, professor of mechanical engineering, Pratt Institute; and David Gregg, administrative engineer, Curtiss-Wright Corporation.

Choice of Rocket Propellants Discussed

THE "sheer perversity of inanimate objects" as manifested by the chemical and physical properties of rocket propellants was discussed with good humor by John D. Clark, at a meeting of the New York Section of the American Rocket Society held in the Engineering Societies Building, New York, N. Y., February 16, 1951. Dr. Clark is head of the Chemistry Section, Naval Air Rocket Test Station, Lake Denmark, N. J. His witty observations captivated the audience. After the talk, "Considerations in the Choice of Rocket Propellant," was concluded many of the young men crowded about him for application forms for jobs in rocket research.

As an extreme example of perversity of a propellant, Dr. Clark mentioned liquid hydrogen, which he said, had much to recommend it. Its boiling point is extremely low and when it liquifies a transition occurs from the ortho to the para state of the molecule which releases heat and accelerates the evaporation. Some of the best oxidizers, such as white fuming nitric acid, approach the legendary solvent in activity. They are more likely than not to attack the storage tanks, eat holes in the fuel tank, and to chew up the pumps unless the materials for these objects are carefully chosen. Even if the corrosion is not mechanically serious, the propellant may be seriously contaminated by the material of its container. Red and white fuming nitric acid can start a brisk fire if it splashes on anything combustible. The fumes given off by the red acid are about as poisonous as phosgene. If the acid touches the skin it can give a nasty burn.

The hydrogen peroxide, he said, will liberate heat which accelerates the decomposition. While not particularly corrosive, hydrogen peroxide will ignite all sorts of things, including wool.

Perversity of Fluorine

Aniline is extremely poisonous and is absorbed through the skin. A splash of it, if not washed off immediately, can easily lead to death. But the propellant that takes first prize for perversity, Dr. Clark said, was fluorine. It evaporates off like liquid oxygen; it is extremely toxic as a vapor; the gas on the skin will produce a dangerous and slow healing burn; and it ignites spontaneously with almost everything, including such alleged noncombustibles as sand and asbestos and such fire-fighting agents as water, carbon dioxide, and carbon tetrachloride.

Because of these troublesome properties, more must be considered in the choice of rocket propellants than energy of reaction. Performance of a propellant combination, usually described in terms of specific impulse, I_{sp}, is a function of the heat release, the total molecular weight of the reactants, and the efficiency of utilization of the energy of the reaction. Efficiency, which influences performances as much as heat release, is affected by certain factors. High chamber pressure increases while high exhaust pressure decreases it. It is known too that low average molecular weight of exhaust gases increases efficiency. Thus a combination that gives a large amount of free hydrogen in the exhaust may actually have a higher specific impulse than a high-carbon combination with a higher heat of reaction per pound.

Many factors other then performance must also be considered. One of these is starting properties of the combination. Some combinations are hypergolic and ignite spontaneously when fuel and oxidizer come in contact. The temperature of reaction must be considered if the motor walls are not to be volatilized. The heat capacity of the fuel (how much heat it can soak up per degree of temperature rise) must be taken in account for stability under all temperature conditions. Density must not be overlooked if tank weight is to be held within reasonable limits.

The Ideal Propellant

Dr. Clark concluded his talk with the following specifications for the ideal all-purpose propellant combinations demanded by rocket engineers:

It should have the specific impulse of plutonium, and be, of course, hypergolic, with an ignition delay of precisely zero. It should have the density, at least, of mercury, and be liquid from absolute zero to at least 1000 C, with no vapor pressure whatsoever. It should have the stability and handling properties of water, and be absolutely innocuous, noncorrosive and nontoxic. It should be suitable for regenerative cooling, with a heat capacity at least that of water, and its viscosity should not only be low, but unchanging over the entire operating range. Its availability should be that of air, but it should be available only in the United States. And as a final consideration, its price should be that of dirt.

Talk on *Viking* Rocket Heard by Indiana Section

INTERESTING information about the high-altitude sounding rocket *Viking* was presented before the Indiana Section of the American Rocket Society at a meeting in the Electrical Engineering Building, Purdue University, West Lafayette, Ind., Dec. 15, 1950, by J. Preston Layton, president of the Section.

Mr. Layton is a graduate student at Purdue University and formerly was in charge of all *Viking* rocket tests at White Sands, N. Mex. He has seen service with the U. S. Navy, and was formerly employed by the Glenn L. Martin Company.

In his talk Mr. Layton discussed specifications of the *Viking*, details of its manufacture and assembly, and described the ground equipment necessary for its firing. From personal experience he was able to give an account of the history of the *Viking* and problems that had to be solved in firing *Vikings* 1, 2, and 3 at White Sands. Slides and motion pictures

at his disposal did much to convey the drama and excitement associated with the firing of the rocket from on board the U.S.S. *Norton*. According to Mr. Layton, research on the *Viking* has been encouraging and was fulfilling requirements. He concluded by saying that engineers interested in rocket technology should take advantage of every opportunity to learn by working with actual rockets.

Dan C. Kimball to Address Section

Prior to Mr. Layton's talk, it was announced that the annual banquet of the Indiana Section would be held in May and that the Honorable Dan C. Kimball, Undersecretary of the Navy, has accepted the invitation to address the section.

Gladys Geiger, Secretary of the Indiana Section, has been doing an exemplary job in keeping Headquarters informed about what is happening on the Purdue campus. The Section is not only stimulating excellent talks on rocket technology, but it is exploring ways in which it can further serve American Rocket Society members in Indiana. Section plans for midwinter and spring dinners are to provide splendid opportunities for members to know one another to exchange information about their projects.

For example, at the December 15th meeting of the Section Board of Directors the topic of publicity came up. The Section wants facts of ARS activities at Purdue more available to students. One idea being explored is the placing of an ARS display in the Purdue Union and the printing of 11 × 17-inch signs to tell about the Indiana Section.

The Section also feels that one of its responsibilities is the placing of rocket literature in the Mechanical Engineering School Library or at least of recommending purchase of publications to the School's committee in charge of such purchasing. The Section is currently compiling a list of rocket publications which it considers a necessary and beneficial acquisition for an engineering library. This list should be available to other ARS Sections and probably should be published in the JOURNAL when completed.

Southern California Section

THE Board of Directors of the Southern California Section met at the Pasadena Athletic Club, Jan. 31, 1951, to evaluate the 1950 Program and to plan events for the Spring.

New officers of the Section are: President, R. B. Canright; Vice-President, B. L. Dorman; Secretary-Treasurer, R. J. Lodge; Members of Board, G. B. Brewer, W. T. Cox, E. E. Coufut, L. G. Dunn, J. F. Manildi, C. C. Ross, and W. E. Zisch.

Among the suggestions for the 1951 program were: That dinner meetings be held; that six meetings be scheduled; that a joint meeting be held with the Institute for the Aeronautical Sciences; and that a classified meeting at the NAA Field Laboratory be investigated.

Note to ARS Secretaries

WHEN your Section invites an interesting and informative speaker to address your Section, do not omit the final courtesy: That of reporting his remarks fully to the editor of the JOURNAL. This act will not only give your Section national publicity but will enable you to share with other ARS Sections the pleasure and benefit of an evening well spent.

It is a good idea to ask your speaker to provide you with a copy of his remarks so that this can be submitted to the JOURNAL along with the regular meeting report form.

If there are any photography enthusiasts among your membership, assign them the task of taking an occasional photograph of the speaker, Section officers, or other members who contribute to the success of your activities.

Aerojet Negotiates New Factory Site

OFFICIALS of the Aerojet Engineering Corporation, Azusa, Calif., a subsidiary of The General Tire & Rubber Company, announced recently that negotiations were virtually completed for the acquisition of a rocket-factory site area

near Sacramento, Calif. The Aerojet Engineering Corporation, one of the world's largest manufacturers of rocket engines, including the famous JATO (jet assisted take-off) motor, has chosen the Sacramento area after a careful survey of many potential plant sites in the West. Negotations for the plant site, for military reasons, were carried out on a secret basis.

The site chosen is the dredged-out area 16 miles east of Sacramento on the south side of Highway 50. The area comprises approximately 7200 acres and is ideally suited for the needs of the rocket factory.

The new factory represents an initial investment of approximately six million dollars, but the site being acquired is sufficiently large to allow for considerable subsequent expansion, if necessary. The initial labor requirements will be approximately 500 persons; the ultimate labor requirements cannot be determined at this time. With the exception of some technical and administrative personnel, all labor will be acquired from the local labor pool.

Aerojet's main plant at Azusa will not be affected by the selection of the new site. Operations at Azusa will continue on the same level as heretofore, with only a portion of its solid propellant operations being moved to Sacramento.

Von Kármán Honored

THEODORE VON KÁRMÁN, Fellow ARS, chairman, Scientific Advisory Board to the Chief of Staff, U. S. Air Force, has been awarded the Kelvin Gold Medal by a special award board consisting of the presidents of the eight major engineering societies of the United Kingdom. This medal is given every third year for outstanding contributions to engineering science, commemorating Lord Kelvin's achievements in this field. The medal was awarded for the first time in 1920; no medal has been awarded, however, between 1938 and 1947. Among the eight scientists who received the medal before are Guglielmo Marconi of wireless fame, the late Nobel Laureate physicist, J. J. Thomson; Sir Frank Whittle, creator of the first turbojet engine. Dr. von Kármán is the second American on the list of medalists, the first being Elihu Thomson, famous pioneer of electrical engineering in the United States, who received the medal in 1923.

In 1942, Dr. von Kármán founded the Aerojet Engineering Corporation, Azusa, Calif., one of the nation's largest developer and manufacturer of rockets, and is that company's chief technical consultant.

He was awarded the Gold Medal of The American Society of Mechanical Engineers in 1941; the Sylvanus Reed Award of the Institute of the Aeronautical Sciences in 1942; the Medal of Merit, the highest civilian award bestowed by the United States government, in 1946; the John Fritz Medal, the highest engineering award given in the United States, for his contribution to engineering and physical research in the fields of aeronautics and the structural sciences, in 1947; and the Franklin Medal in 1948 in recognition of outstanding engineering and mathematical achievements, particularly those relating to development of advanced aerodynamic conceptions and aeronautical design.

In addition to memberships in most of the learned and technical societies of the United States, Dr. von Kármán is a member of the Royal Society of London; the French Academy of Sciences; the Academy of Sciences, Madrid; the Academy of Torino; and the Accademia dei Lincei, Rome. He is an Officer of the French Legion of Honor.

Dr. von Kármán has honorary degrees from Princeton and the University of California; the University of Berlin; Liége University and the University of Brussels, Belgium; and the University of Marseille, France.

ARS to Meet With ASME at Toronto

THE American Rocket Society is planning to sponsor one or two technical sessions at the 1951 Semi-Annual Meeting of The American Society of Mechanical Engineers to be held at the Hotel Royal York, Toronto, Ontario, Can., June 11–15, 1951.

ARS Junior Award

THE distinction of receiving an American Rocket Society Junior Award carries with it a recognition of meritorious achievement early in one's professional career. Papers are now being accepted at the New York Office for consideration for the 1951 Award. The award and medal will be presented at the Annual Convention to be held in December. To be considered, papers should be submitted not later than Oct. 15, 1951.

The winning paper will be judged mainly on the basis of content which should reflect original thought and effort. The age of authors of papers is limited to twenty-five. Papers should be on standard size paper, typewritten, and clearly marked: Submitted for Junior Award Competition. Send papers to: Secretary, American Rocket Society, 29 West 39th Street, New York 18, N. Y.

Jobs for Rocket Engineers

THE U. S. Naval Ordnance Test Station, Inyokern, Calif., is currently recruiting electronic engineers and mechanical engineers with ordnance experience for a variety of positions involving aspects of research, development and testing of rockets and guided missiles. Applications are desired from qualified engineers with an engineering degree, or its equivalent, and several years' experience in research and ordnance engineering. Experience is especially desired in such fields as servomechanisms, electronic computers, radar, automatic control systems, circuit analysis, telemetering, and similar fields related to ordnance testing.

Most positions to be filled are at $5400 salary level.

Interested persons qualified to fill these positions should contact the Personnel Department, U. S. Naval Ordnance Test Station, Inyokern, China Lake, Calif., or the Navy Department Joint Board of U. S. Civil Service Examiners in Pasadena, Calif.

Available ARS Preprints

Preprint No.:	*Title and author*
15-50	A General Method for the Calculation of Theoretical Performance of Rocket Engines, by V. N. Huff
16-50	Stability of Liquid Films for Cooling Rocket Motors, by M. J. Zucrow, C. M. Beighley, and E. L. Knuth
17-50	Notes on the Behavior of Supersonic Gases in Overexpanded Nozzles, by K. Scheller and J. A. Bierlein
18-50	Optimum Thrust Programming for a Sounding Rocket, by H. S. Tsien and Robert C. Evans
19-50	Heat Recovery and Maximum Thermodynamic Efficiency in a Rocket, by J. J. Ward and J. W. Clegg
20-50	Naval Air Rocket Test Station—Purpose and Progress, by Lt. Comdr. F. C. Durant, 3d
21-50	Operations with the High Altitude Sounding Rocket *Viking*, by J. P. Layton
22-50	Rocket Engine Flight Testing, by R. F. Gompertz
23-50	Micro-Scale Rocket Studies, by Bradford Darling and Saul Wolf
24-50	Some Measurements of the Burning Rates of Mixed Liquid Bi-Propellants, by C. W. Tait, A. G. Whittaker, and H. Williams
25-50	Principles of Rocket Turbopump Design, by C. C. Ross
26-50	Throttling Thrust Chamber Control, by M. Meyer
27-50	Expellant Bags for Rocket Propellant Tanks, by W. R. Sheridan

Order copies from American Rocket Society, 29 West 39th Street, New York 18, N. Y.